WWW.ANL.GOV/D3

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ADVANCED TECHNOLOGY VEHICLE LAB BENCHMARKING (LEVEL 1 & LEVEL 2)

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Vehicle System Research Group,
Advanced Powertrain Research Facility,

2017 U.S. DOE Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, June 6th, 2017

Project ID# GI030

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

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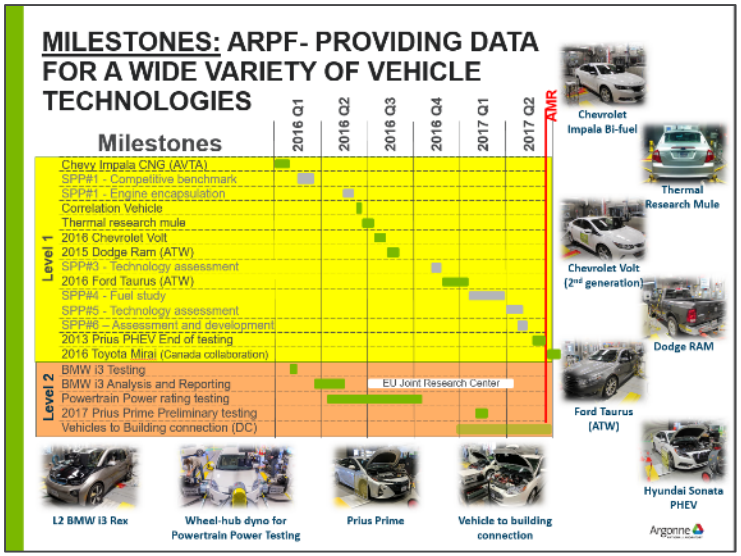
OVERVIEW

Timeline

- Benchmarking at ANL started in 1998
- FY16 Completed Testing:
- FY16 Test Vehicles
  - See Milestone on slide 6



Budget

- FY16 $1,600k
- FY17 $1,300k (to-date)

DOE VSST barriers addressed:

- Computational Models, Design and Simulation Methodologies (C)
  - Model development and validation
- Lack of Standardized Testing Protocols (D)
  - Validating HEV, BEV & PHEV procedures
  - Support of SAE committee (J2951 Drive Metrics, J2907/2908 Powertrain rating, J2263 Coast Down, etc…)
- Constant Advances in Technology (F)
  - Public data generation from benchmarking recent mass-produced BEVs and PHEVs.
  - Advances in HEVs and Alt Fueled Vehicles compared to previous models

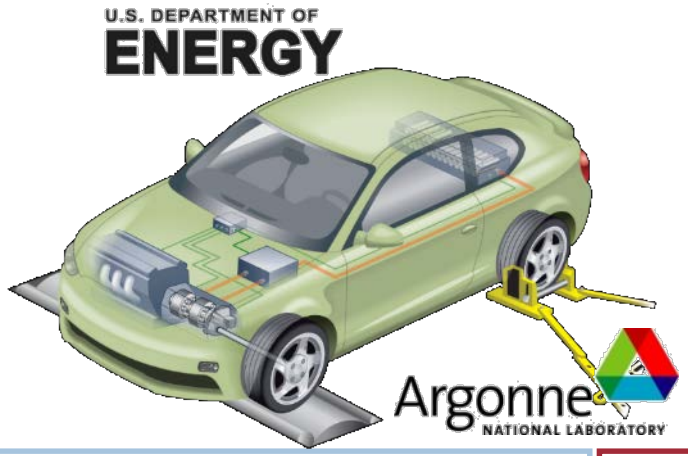
Partners:

- AVTA (Advanced Vehicle Testing Activity): DOE, INL, Intertek CECET, ANL
- DOE, National Laboratories, USDrive, OEMs, Component Suppliers, Vehicle Competitions
- EPA, CARB, Environment Canada

RELEVANCE: OBJECTIVES OF THE ADVANCED POWERTRAIN RESEARCH FACILITY (APRF)

Technology Assessment

Assess state-of-the-art transportation technology for the Department of Energy and Argonne research interests



Codes and Standards

No adpotion unless new technology test method provides fair and accurate results

Research Oriented Test Facilities

4WD chassis dynamometer

- Thermal Chamber: 0F to 95F
- Solar emulation

2WD chassis dynamometer

- Up to medium duty

Vehicle Technology Assessment

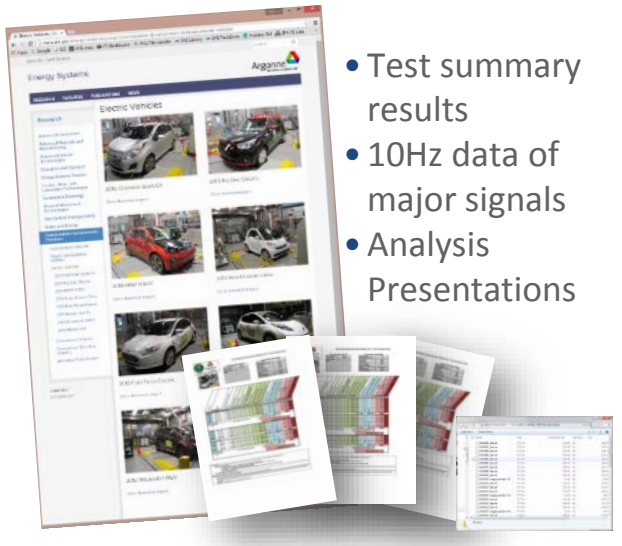
Vehicle level

- Energy consumption (fuel + electricity)
- Emissions
- Performance
- Vehicle operation and strategy

'In-situ' component & system testing

- Component performance, efficiency, and operation over drive cycles
- Component mapping

Downloadable Dynamometer Database www.anl.gov/d3



- Test summary results
- 10Hz data of major signals
- Analysis Presentations

RELEVANCE: HIGHLY LEVERAGED DATA AND ANALYSIS YIELD REAL OUTCOMES

Openly shared public data on advanced technology vehicles is very rare. The data may exist within the largest industry labs, but this data is confidential and closely guarded.

APRF

Independent and Public Data and Analysis

Dynamometer Downloadable Database

www.anl.gov/D3/

DOE Partner Data Sets

Full data sets with more signals and more tests available

Analysis and Insights

→ Quantifies technology challenges

→ Leads to innovation in basic research

→ **Enable petroleum displacement through technology assessment & data dissemination**

Technology Assessment

- Technology trends at component and system level
- Inform research goals
- Find efficiency opportunities

Modeling and Simulation

- Component mapping
- Thermal analysis
- Climate control system
- Data for validation

Codes and Standards

- Procedures development and validation
- Technology neutral
- Informed decision making

Independent Public Data and Knowledge Base

- Academia, national laboratories, startups, suppliers, and OEMs

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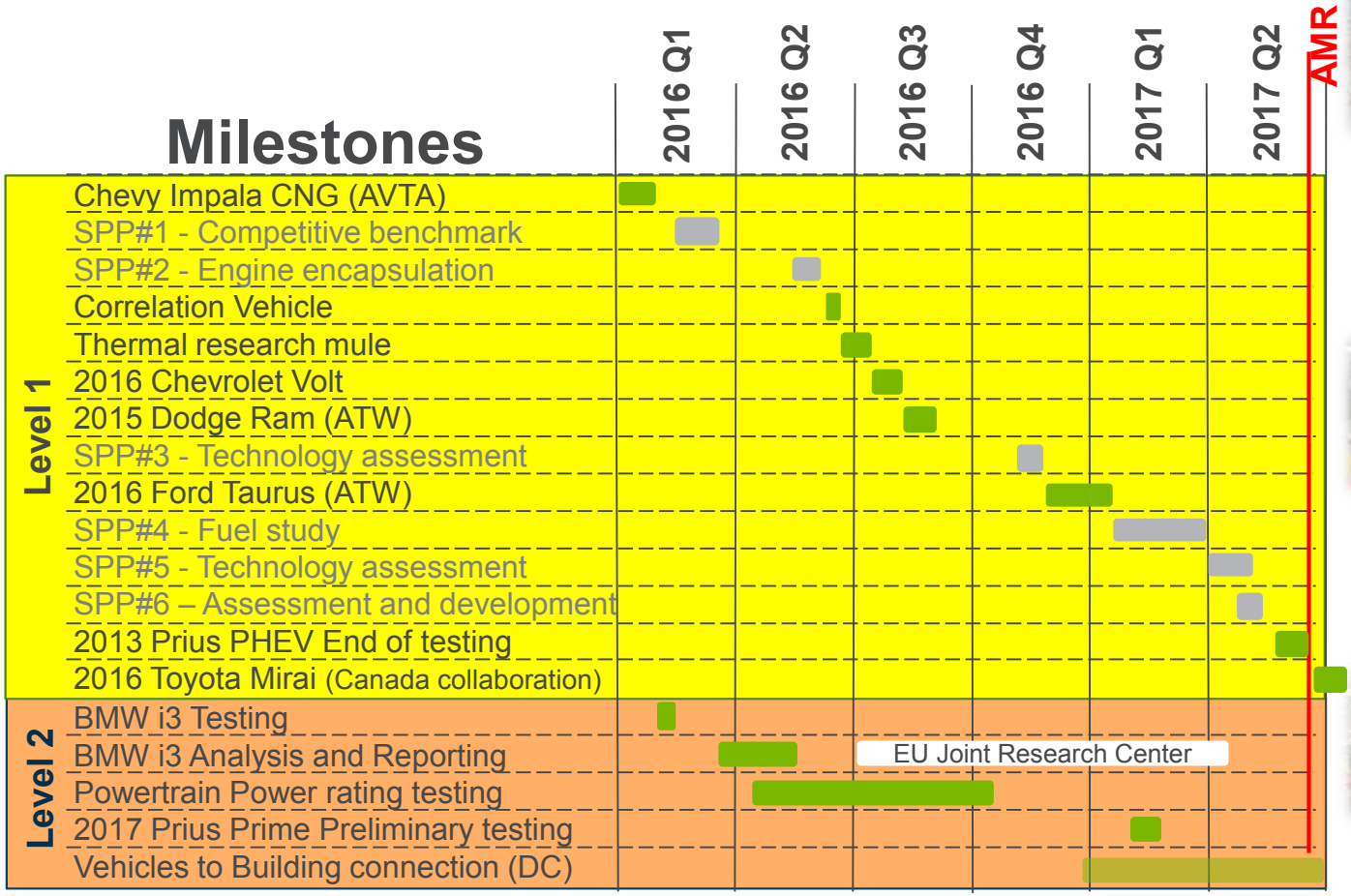
MILESTONES: APRF- PROVIDING DATA FOR A WIDE VARIETY OF VEHICLE TECHNOLOGIES



Chevrolet Impala Bi-fuel

Thermal Research Mule

Chevrolet Volt (2nd generation)

Dodge RAM

Ford Taurus (ATW)

Hyundai Sonata PHEV

L2 BMW i3 Rex

Wheel-hub dyno for Powertrain Power Testing

Prius Prime

Vehicle to building connection

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APPROACH: WELL-ESTABLISHED AND EFFECTIVE TEST METHODS ADJUSTED TO INDIVIDUAL TECHNOLOGIES

The vehicle benchmark activity has been refined during the past decade, which has resulted in:

- Advanced and unique facilities and instrumentation
- Continuous improvement of testing procedures
- Standardization of test plans including instrumentation and drive cycles which are adjusted for individual vehicles
- Significant knowledge of advanced vehicles and testing methods

APRF expertise in testing

Powertrains

- Conventional
- Hybrid Electric (HEV)
- Plug-in HEV (PHEV)
- Battery Electric (BEV or EV)
- Fuel Cell Vehicle

Alternative fuels

- Hydrogen, Natural Gas
- Ethanol, Butanol
- Diesel (Bio, Fisher-Tropsch)

Test Process:

New vehicle

New technology? Specific questions? Modeling needs? Larger study?

→

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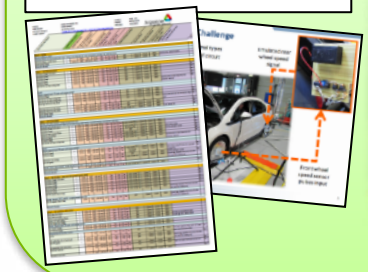
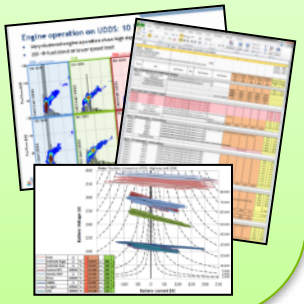
Baseline Dynamometer Testing

1. Preparation and instrumentation



2. Dyno testing

3. Analysis



→ Data and Analysis →

National Labs USCAR (OEMs)

ornl INL Argonne NREL USDRIVE

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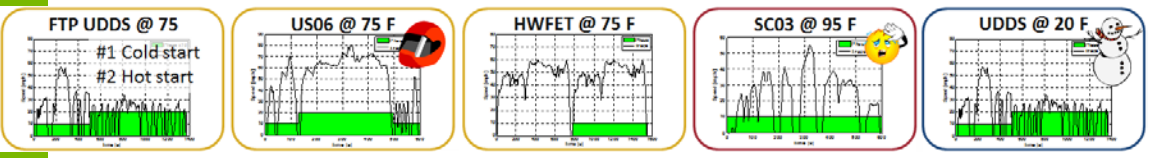
APPROACH: PURPOSE BUILT RESEARCH LABORATORY FOR AUTOMOTIVE TECHNOLOGY EVALUATIONS

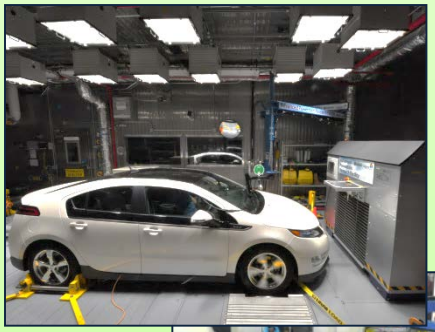
- Level 1 and Level 2: Comprehensive instrumentation and evaluation
  - Level 1: Systems level, **reversible!**
  - Level 2: Focused, component and systems level
  - Vehicle characterization (fuel and energy consumption, emissions, performance)
  - Vehicle operation and strategy
  - Component specific instrumentation for analysis and modeling (speed, temp, and other technology specific removable instrumentation)
- Drive cycles and test conditions
  - Standard drive cycles **+ technology specific cycles, performance tests, vehicle and component mapping cycles**
  - Thermal test conditions: 0^0F to 95^0F with 850 W/m^2 radiant solar energy (full "5-Cycle")
  - Additional testing at 0^0F and 40 ^{0}F as desired



Advanced Powertrain Research Facility

The right tools for the task:

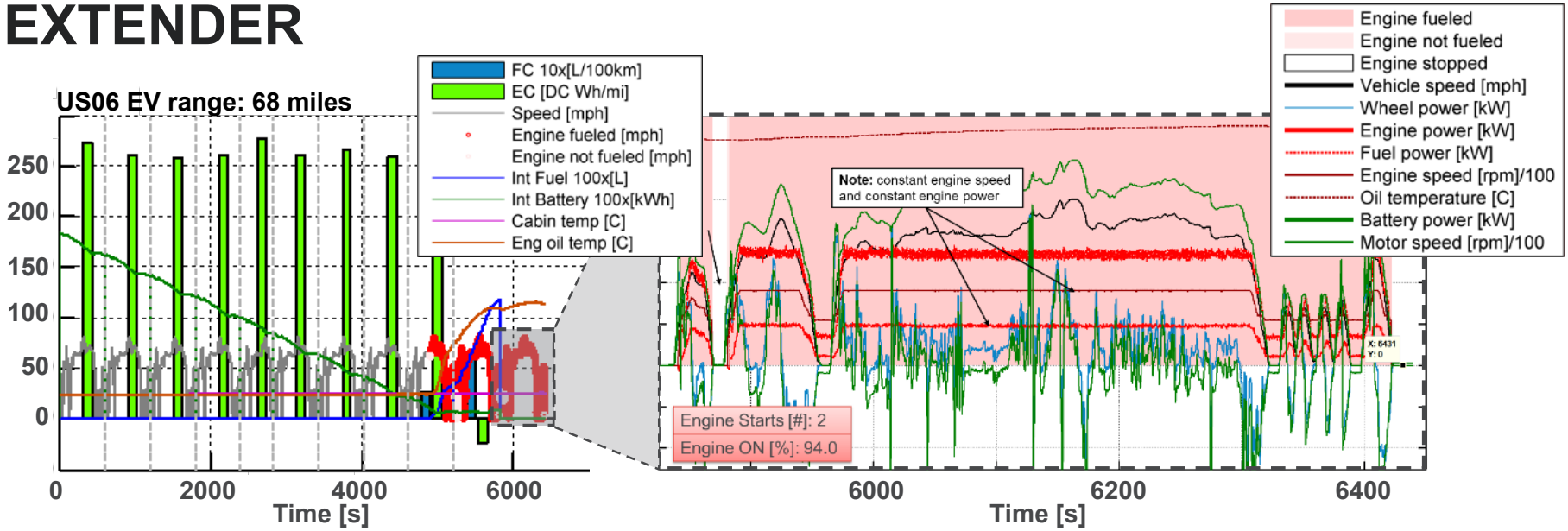
- *Two chassis dynamometer cells*
- *Custom DAQ, flexible, module-driven, used in both cells*
- *Thermal chamber which is 5-Cycle compliant (+)*

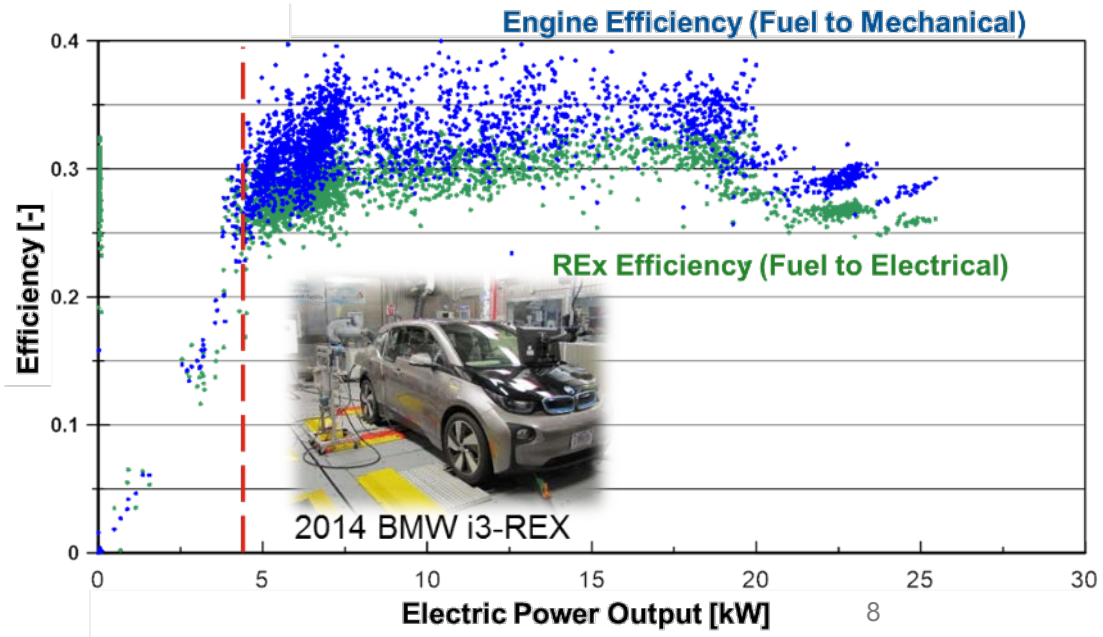


4WD chassis dyno with thermal chamber

2WD chassis dyno

ACCOMPLISHMENTS: LEVEL 2 BMW I3 RANGE EXTENDER





Engine Operation Observations:

- Two major operating speeds:
  - 2400 rpm for 5-8 kW
  - 3550 rpm for 10-20 kW
- 25kW max power at 4500 rpm which may not be sufficient in certain conditions

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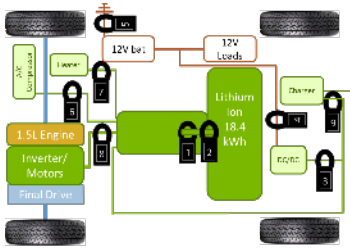
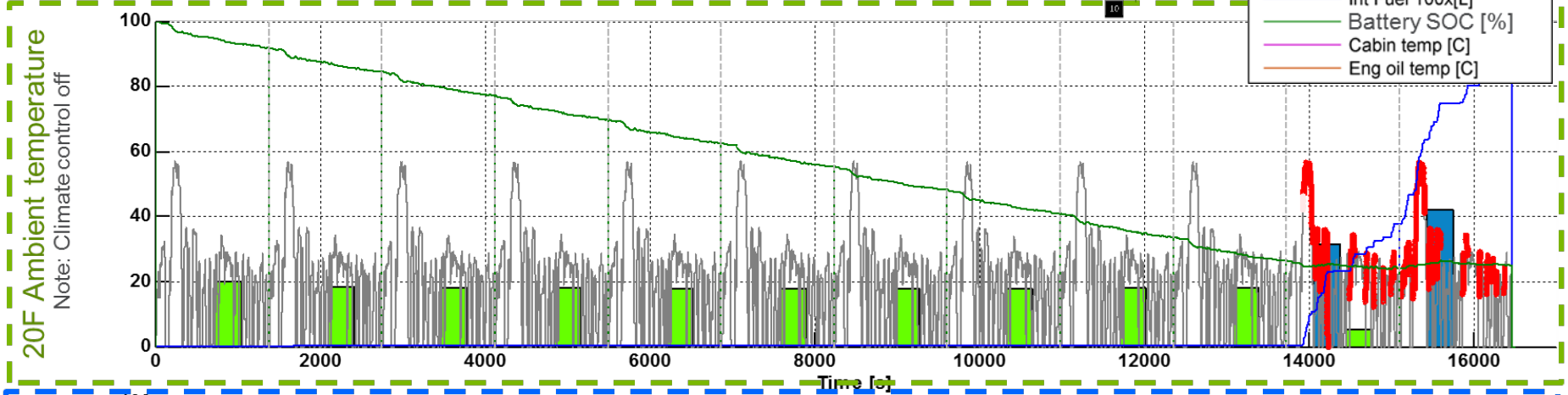
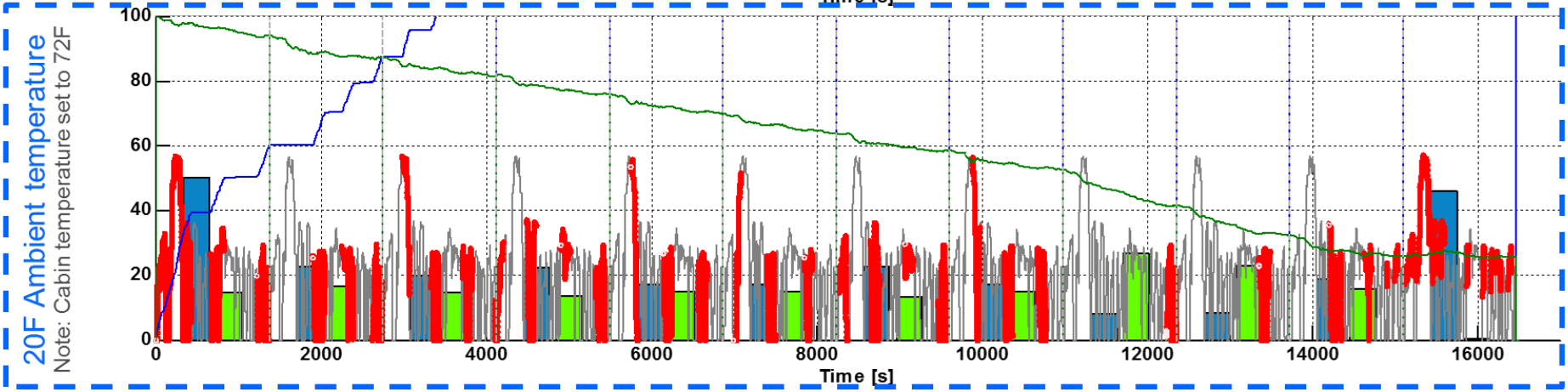
ACCOMPLISHMENTS: 2016 CHEVROLET VOLT

2016 Volt



	Clamp Location	Range (A)
1	HV Battery (midpack)	500
2	HV Battery (midpack)	200
3	DCDC In	20
4	DCDC out	200
5	12V Battery	200 st 80
6	AC Compressor	20
7	PTC Heater	20
8	Inverter/ Motor	200
9	Charger out	200
10	AC Charge in	20





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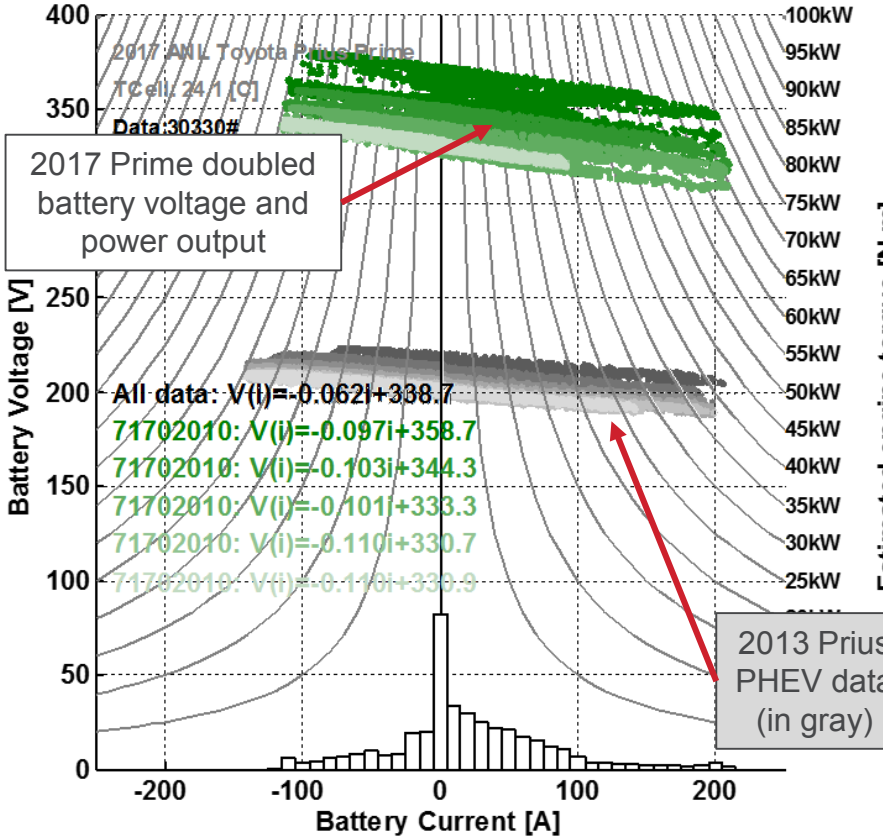
ACCOMPLISHMENTS: 2017 PRIUS PRIME TECHNOLOGY ASSESSMENT

2017 Prius Prime

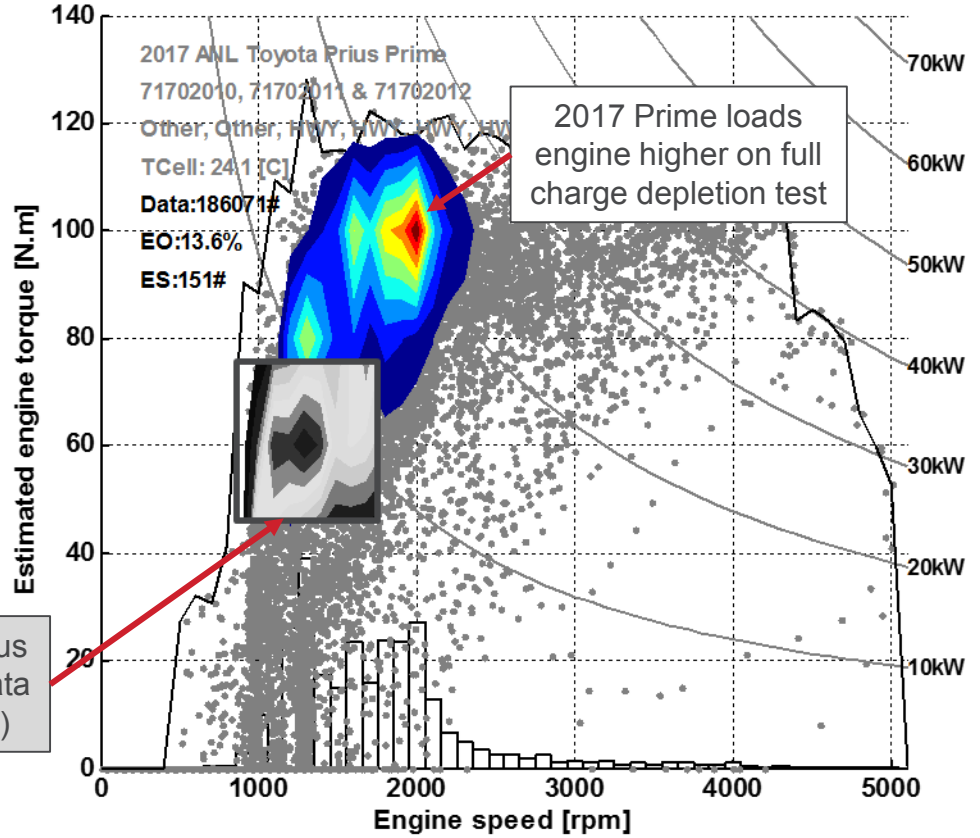
Preliminary data (72F):
EV in charge depleting
Comparison to 2013 Prius PHEV
Thermal limitations of air cooled battery

Level 2 In-depth & invasive benchmark:
Technology assessment
Evaluation of automated driving features
Explore vehicle to grid connection



2017 Prime doubled battery voltage and power output

2013 Prius PHEV data (in gray)



2017 Prime loads engine higher on full charge depletion test

Data from FCT UDDS + FCT Highway + FCT US06 @ 72F

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ACCOMPLISHMENTS: BLENDED PHEV PETROLEUM DISPLACEMENT POTENTIAL BASED ON DRIVE STYLE

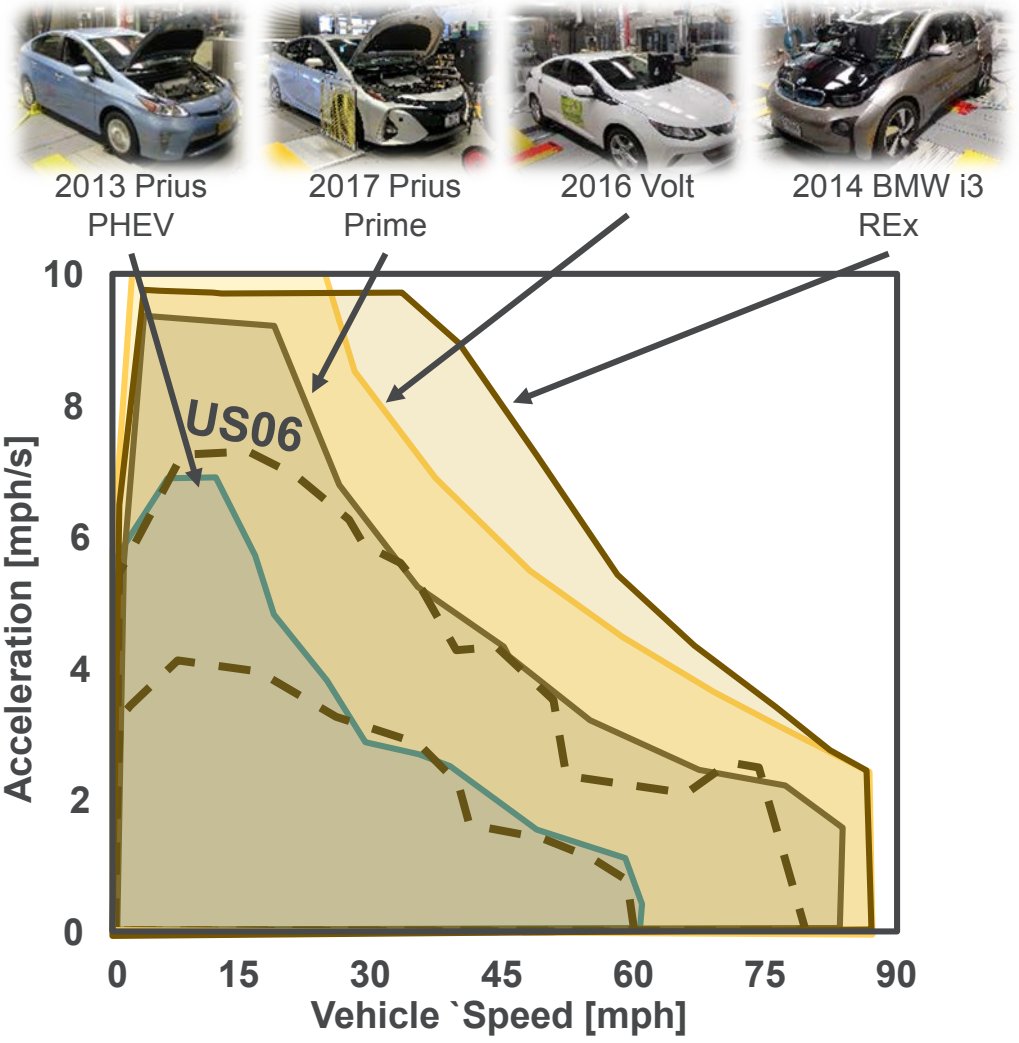
The petroleum displacement of different PHEVs depends on the size of the EV envelop and how well it matches the driving requirements while in charge depleting mode.

Blended PHEVs

– Engine starts may occur due to high power demands from
  - Heavy accelerations
  - High speed operation (Speeds at which people drive)
  - Thermal reason (cabin heat, exhaust after treatment)

EREV and BEVx

– Engine will not come ON in charge depletion mode (except thermal perhaps)
  → 100% Petroleum Displacement until depletion (@ 72F)



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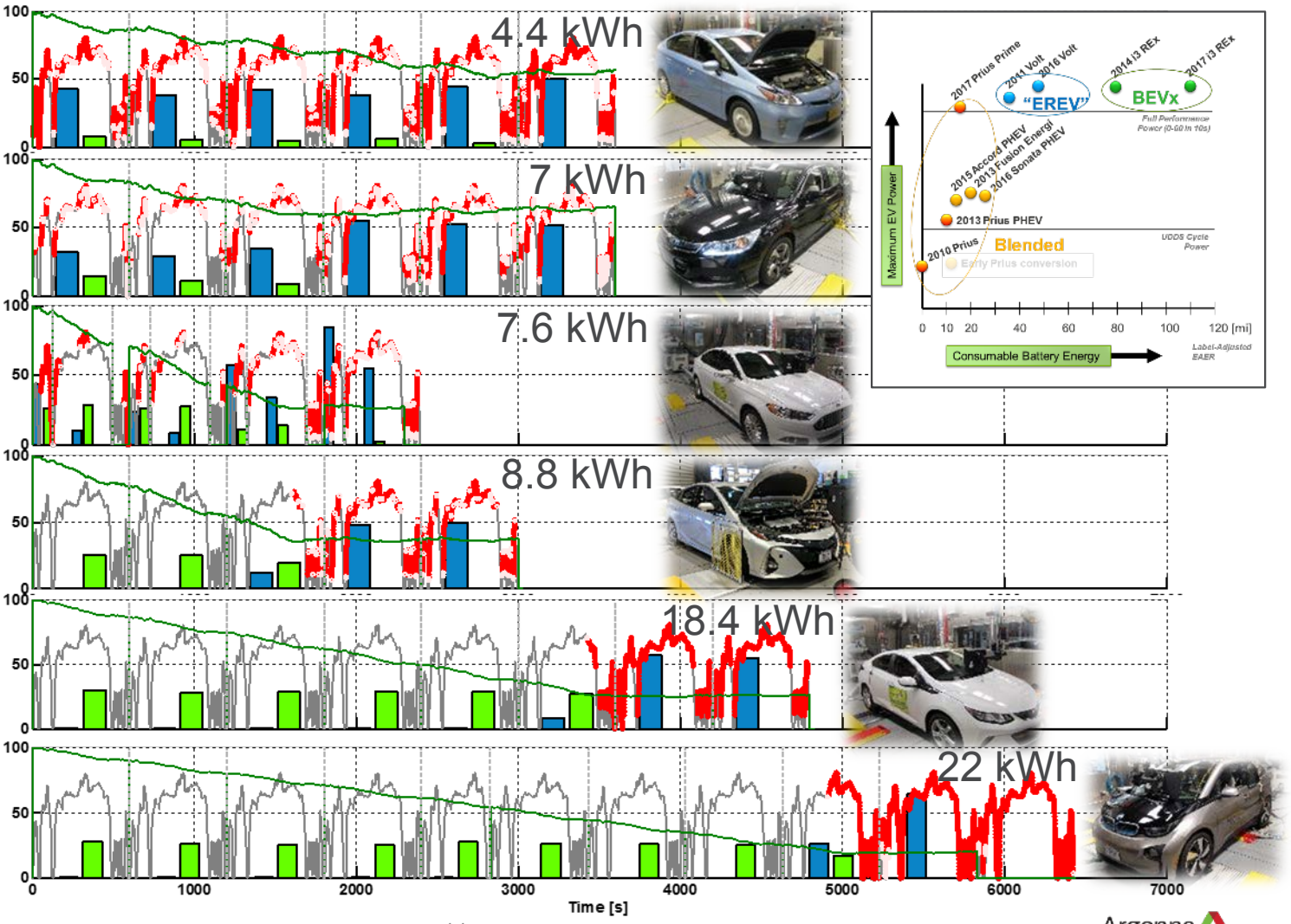
ACCOMPLISHMENTS: BLENDED PHEV PETROLEUM DISPLACEMENT POTENTIAL BASED ON DRIVE STYLE

Vehicles
2013 Prius PHEV
2015 Accord PHEV
2013 Fusion Energi
2017 Prius Prime
2016 Volt
2014 BMW i3 REX



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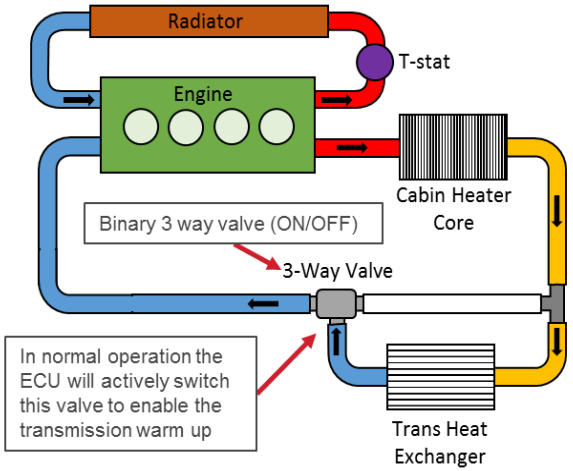
ACCOMPLISHMENTS: ACTIVE TRANSMISSION WARM UP RESEARCH

2013 Ford Taurus

Active Transmission Warm-up On



Test required

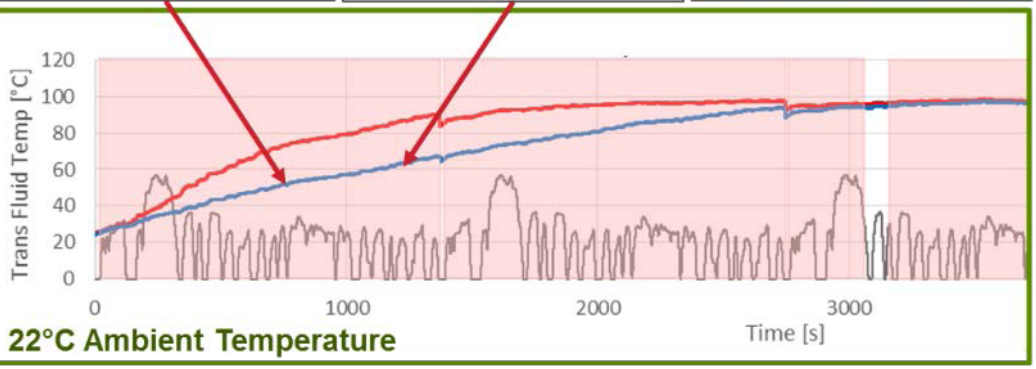
Robot driver

Statistical confidence
Consistency
Multi-cycle traces
Instrumentation
Variability experience

"ATW Auto" → the ECU decides the position of the three way valve (normal operation)

"ATW Off" → transmission heat exchanger is always by-passed (3-way valve disabled)

Pink background indicates that engine coolant pass through the transmission heat exchanger



Conclusions

Measuring small changes in fuel consumption is difficult, but the APRF is well equipped for that task.

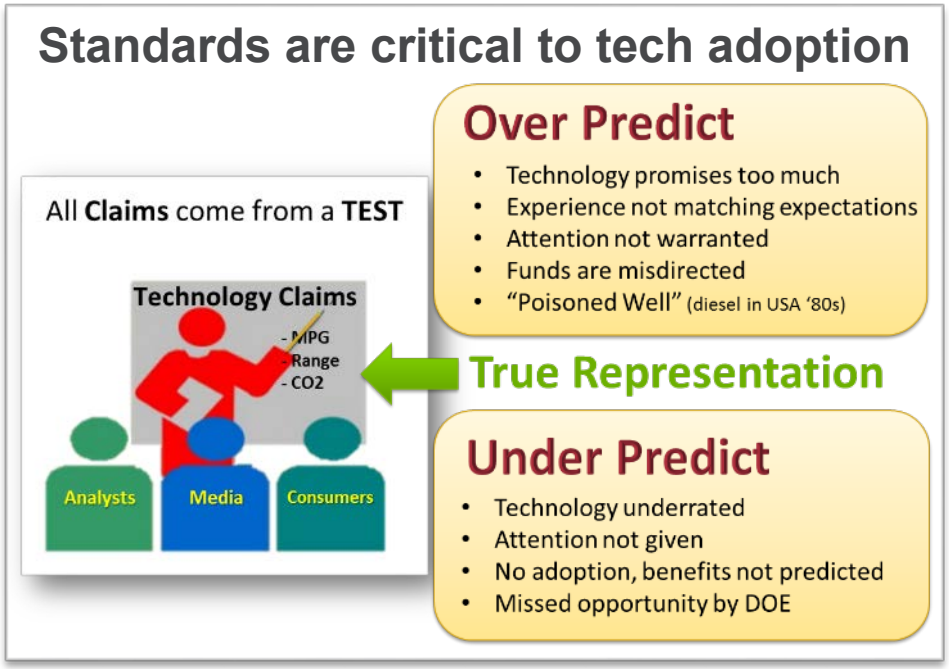
FTP	FC benefit [%]	Trans. temp. diff [C]
UDDS @ 22C	1.45%	23°C
UDDS @ -7C	1.28%	13°C

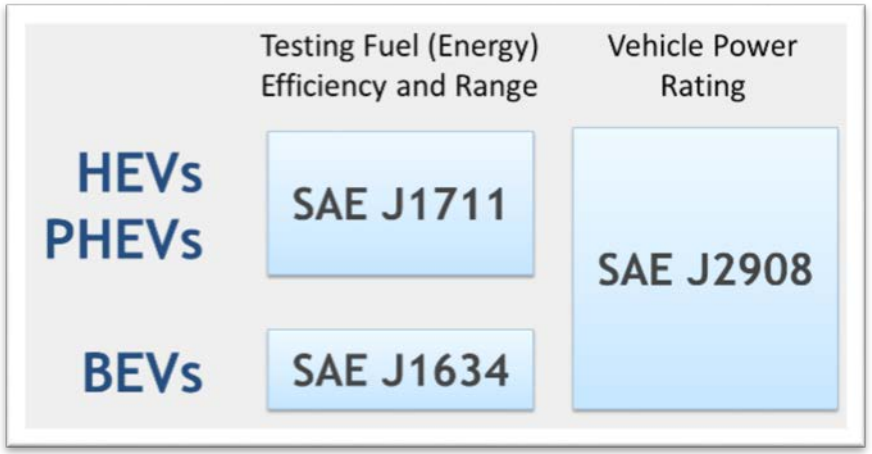
5 cycle	FC Benefit [%]	CO_2 Benefit [g/mi]
FC City	0.85	4.10
FC Hwy	0.08	0.29
FC Comb	0.56	2.39

→ While statistically significant, the results above are only for this particular car with this particular active transmission warm up system

ACCOMPLISHMENTS: LEADERSHIP IN GLOBAL PERFORMANCE AND EFFICIENCY STANDARDS

- SAE J2908 Hybrid System Power Rating
  - Chaired task force (start: 2015), ran tests, authored document
  - Status: now ready for ballot
  - International: Harmonize with ISO WD20762, co-ordinate with UN GTR
- SAE J1634 Electric Vehicle Efficiency and Range
  - Contributor to 2017 re-issue, refinement to save test burden
  - In-person, and public "thank-you" from a GM Director
- SAE J1711 HEV/PHEV Efficiency and CD Range (Planned revision in 2017/2018)
- SAE J2262/J2263 Coastdown and Roadload (Developed new roadload measurement methods, useful for CAVs)
- Research on Reconciling Dyno, On-road, "Real World" Tests





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COORDINATION: EXISTING COLLABORATIONS WITH OTHER INSTITUTIONS

J1711 HEV & PHEV test procedures
J1634 EV test procedures
SAE International

International
- Joint Research Centre (EU)
- KATECH (Korea)
- CAERI
- ISO
- JARI (Japan)
- IEA

AVTA (Advanced Vehicle Testing Activity)
Baseline dynamometer testing of vehicles
INL Idaho National Laboratory, Argonne National Laboratory, Intertek cecet

APRF

DOE technology evaluation
•DOE requests
•National Lab requests
NREL, ornl, INL Idaho National Laboratory, Argonne

AVTC (Advanced Vehicle Technology Competition
Universities
AVTC, GM, EcoCAR2 PLUGGING IN TO THE FUTURE

USCAR, tech teams and OEMs
Shared test plans, data and analysis
USDRIVE DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Autonomie
Support of modeling and simulation with data
AUTONOMIE

Chrysler CHRYSLER
GM GM
Ford Ford

PROPOSED FUTURE WORK: 20 YEARS OF CONTRIBUTIONS TO RAPIDLY IMPROVING AUTOMOTIVE TECHNOLOGIES

Facilities and tools

- Downloadable Dynamometer Database
- AVTC Testing @ EPA
- Modular Automotive Technology Testbed
- CAN decoding
- Modular DAQ
- Robot driver
- PEMS
- Vehicle to grid
- Vehicle as sensor
- Clayton chassis rolls
- 4WD chassis dyno
- Hydrogen capable
- 2WD chassis dyno
- Thermal Chamber
- 4WD CAVs upgrade

1998 2000 2002 2004 2006 2008 2010 2012 2014 2016

HEV Era **Plug-in Era** **CAVs Era**

Achievements

- 99 Japan Prius – component and control
- In-situ engine mapping
- Emulated battery in PHEV-FCV
- BMW Hydrogen 7
- All PHEV conversions
- OEM PHEVs
- X-prize
- Stranded Energy
- Thermal impact on HEV, BEV
- Thermal mule and cart
- Thermal management
- ACC testing

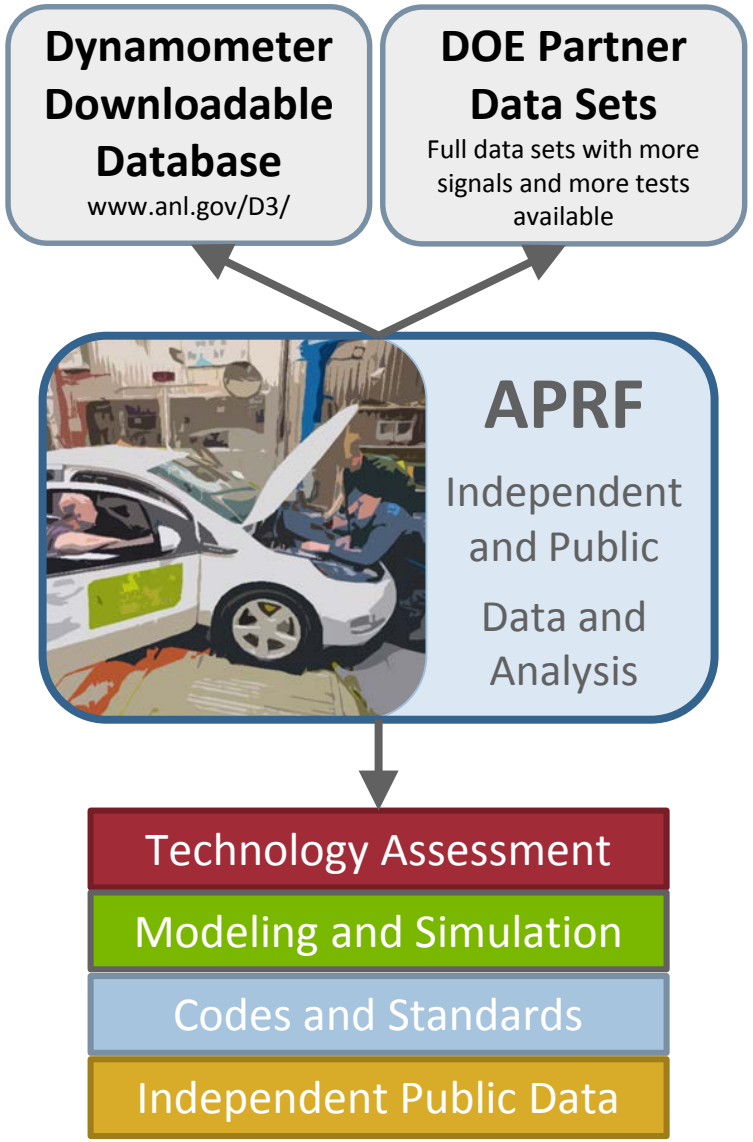
SAE J1711 / J1634 / J2951 / J2608 / J2908 /….

Continued Technology Assessment (CVs, HEVs, PHEVs, BEVs, Alt fuel)

Any proposed future work is subject to change based on funding levels

SUMMARY

- **APRF Vehicle Technology Evaluation Activity** continues to provide precise laboratory test data for a wide range of vehicle technologies that address DOE goals
- **Highlighted Accomplishments from Vehicle Technology Evaluation**
  - BMW i3 range extender investigation, 2016 Chevy Volt, 2017 Toyota Prius Prime
  - A blended PHEV study and an active transmission warm up study
  - Significant contributions to global automotive testing standards
  - Test results and raw data available publicly at the Downloadable Dynamometer Database website (http://www.transportation.anl.gov/D3/)
- **Continued Link to Industry** is an important component of vehicle testing
  - Industry technology experts provide insight into what data is of interest, and assist in aiming testing direction
  - The APRF relies on technology assessment and research contracts from industry



TECHNICAL BACK-UP SLIDES

ADVANCED POWERTRAIN RESEARCH FACILITY
4WD CHASSIS DYNAMOMETER THERMAL TEST CELL

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U.S. DEPARTMENT OF ENERGY

"Research and Data Driven Lab"
"Independent Public Data"

• Test cell features

- ✓ 4WD chassis dynamometer
  - Variable wheel base (180inches max)
  - 250 hp/axle
  - 300 to 12,000 lbs.. inertia emulation
- ✓ Radiant sun energy emulation 850W/m^2 (adjustable)
- ✓ Variable speed cooling fan (0–62mph)
- ✓ Gaseous fuel and hydrogen capable
- ✓ Diesel: Dilution tunnel, PM, HFID

• Thermal chamber

- ✓ EPA 5 cycle capable (20°F, 72°F and 95°F + 850W/m^2 solar load)
- ✓ Demonstrated as low as 0°F
- ✓ Intermediate temperatures possible

• Research aspects

- ✓ Modular and custom DAQ with real time data display
- ✓ Process water available for cooling of experiment components
- ✓ Available power in test cell
  - 480VAC @ 200A
  - 208VAC @ 100A
- ✓ ABC 170 Power supply capable to emulate electric vehicle battery
- ✓ Custom Robot Driver with adaptive learning
- ✓ Several vehicle tie downs
  - chains, low profile, rigid,…
  - 2, 3 and 4 wheel vehicle capable
- ✓ Expertise in testing hybrid and plug-in hybrid electric vehicles, battery electric vehicles and alternative fuel vehicles

• Special instrumentation

- ✓ High precision power analyzers (testing and charging)
- ✓ CAN decoding and recording
- ✓ OCR scan tool recording
- ✓ Direct Fuel Flow metering
- ✓ Infra Red Temperature camera
- ✓ In cylinder pressure indicating systems
- ✓ In-situ torque sensor measurement
- ✓ 5 gas emissions dilute bench with CVS (modal and bag emissions analysis)
- ✓ FTIR, Mobile Emissions unit
- ✓ Raw and Fast HC and NOx bench
- ✓ Aldehyde bench for alcohol fuels

***APRF** (Advanced Powertrain Research Facility)*

ADVANCED POWERTRAIN RESEARCH FACILITY
2WD CHASSIS DYNAMOMETER

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U.S. DEPARTMENT OF ENERGY

"Research and Data Driven Lab"
"Independent Public Data"

• Test cell features

- ✓ 2WD Light Duty / Medium Duty chassis dynamometer
  - 300 hp
  - 300 to 14,000 lbs.. inertia emulation
  - 10,000 lbs.. max weight driven axle
- ✓ Multiple cooling fans available
- ✓ Vehicle lift (max 10,000 lbs..)
- ✓ Remotely located control room with conference area

• Research aspects

- ✓ Modular and custom DAQ with real time data display
- ✓ Flexible to adopt any drive cycle
- ✓ Available power in test cell
  - 480VAC @ 200A & 100A
  - 208VAC @ 50A, 30A & 20A x3
- ✓ ABC 170 power supply capable to emulate electric vehicle battery
- ✓ Custom Robot Driver with adaptive learning
- ✓ Expertise in testing hybrid and plug-in hybrid electric vehicles, battery electric vehicles and alternative fuel vehicles

• Special instrumentation

- ✓ High precision power analyzers (testing and charging)
- ✓ CAN decoding and recording
- ✓ OCR scan tool recording
- ✓ Direct Fuel Flow metering
- ✓ Infra Red Temperature camera
- ✓ In cylinder pressure indicating systems
- ✓ In-situ torque sensor measurement
- ✓ SEMTECH-DS (Mobile Emissions unit) with AVL DVE mass flow sensor

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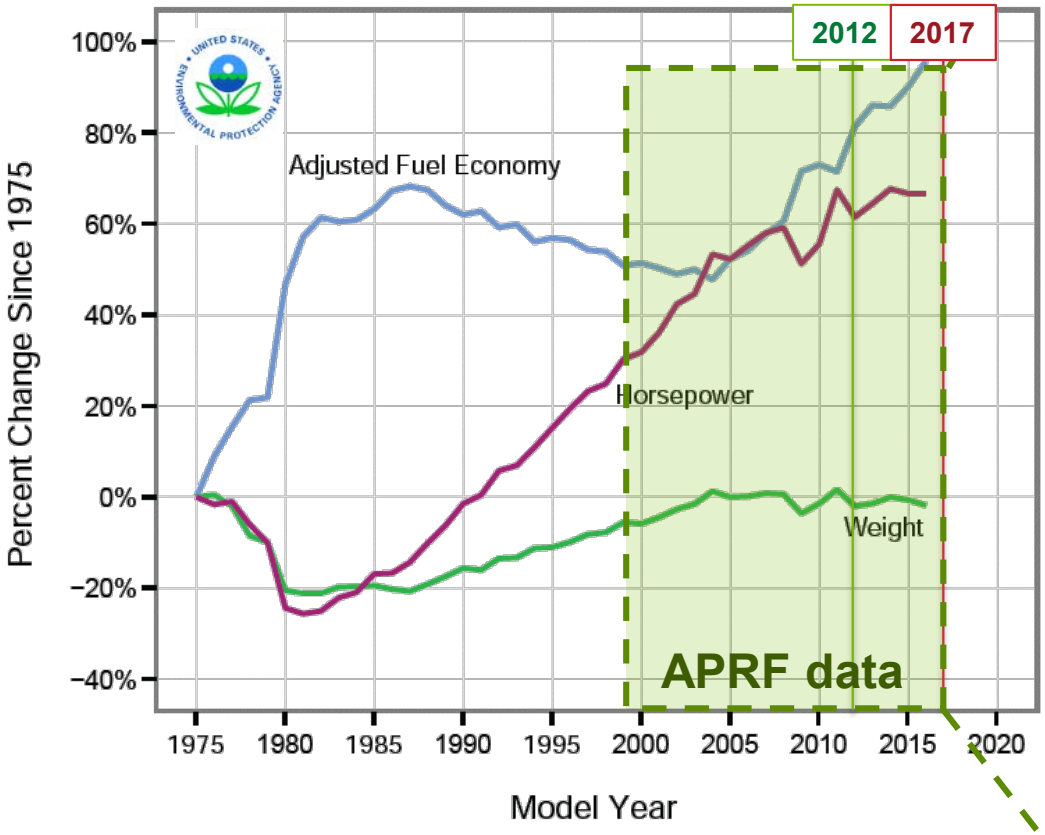
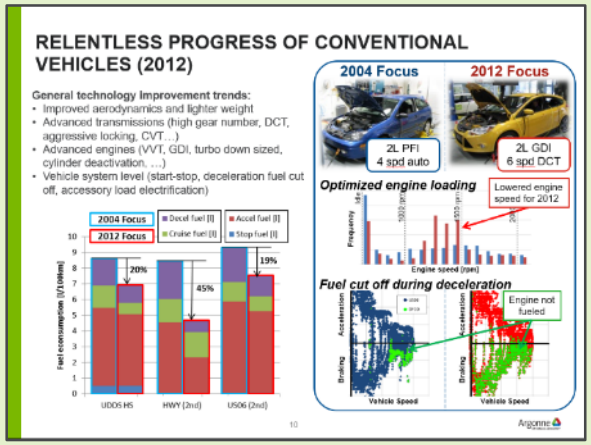
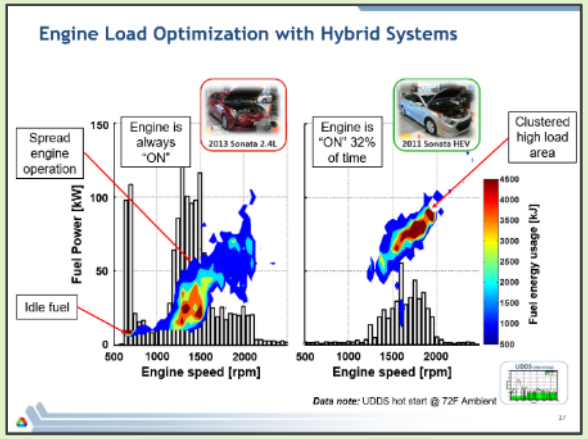
ver. Jan2012

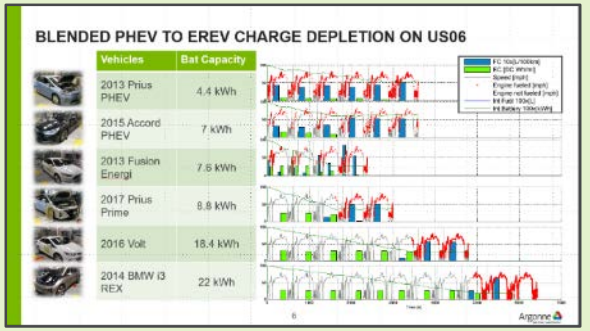
APRF PROVIDES INSIGHTS BEYOND THE EPA NUMBERS



EPA report updated annually:
www.epa.gov/oms/fetrends.htm







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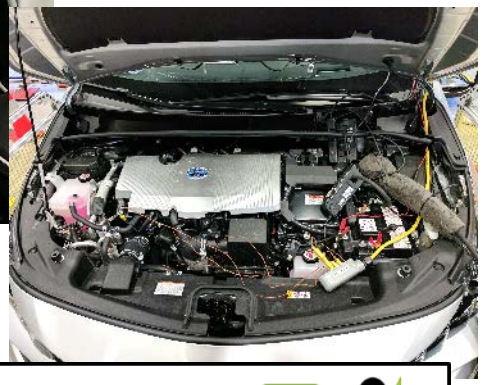
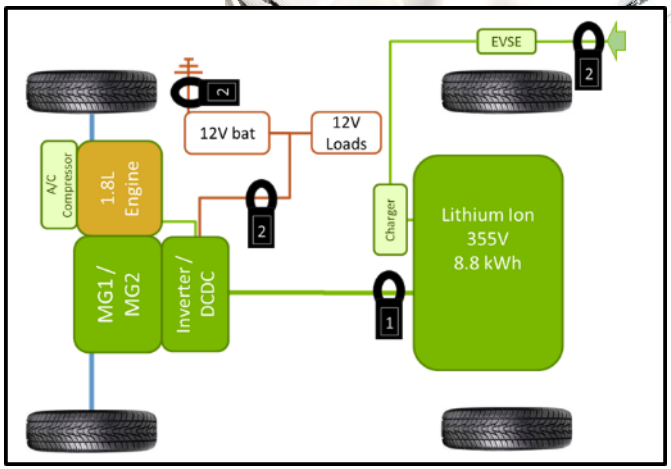
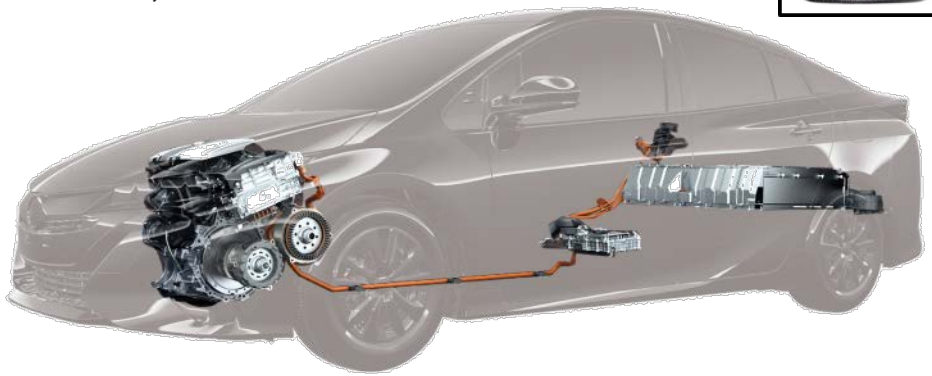
2017 TOYOTA PRIUS PRIME



Vehicle features:

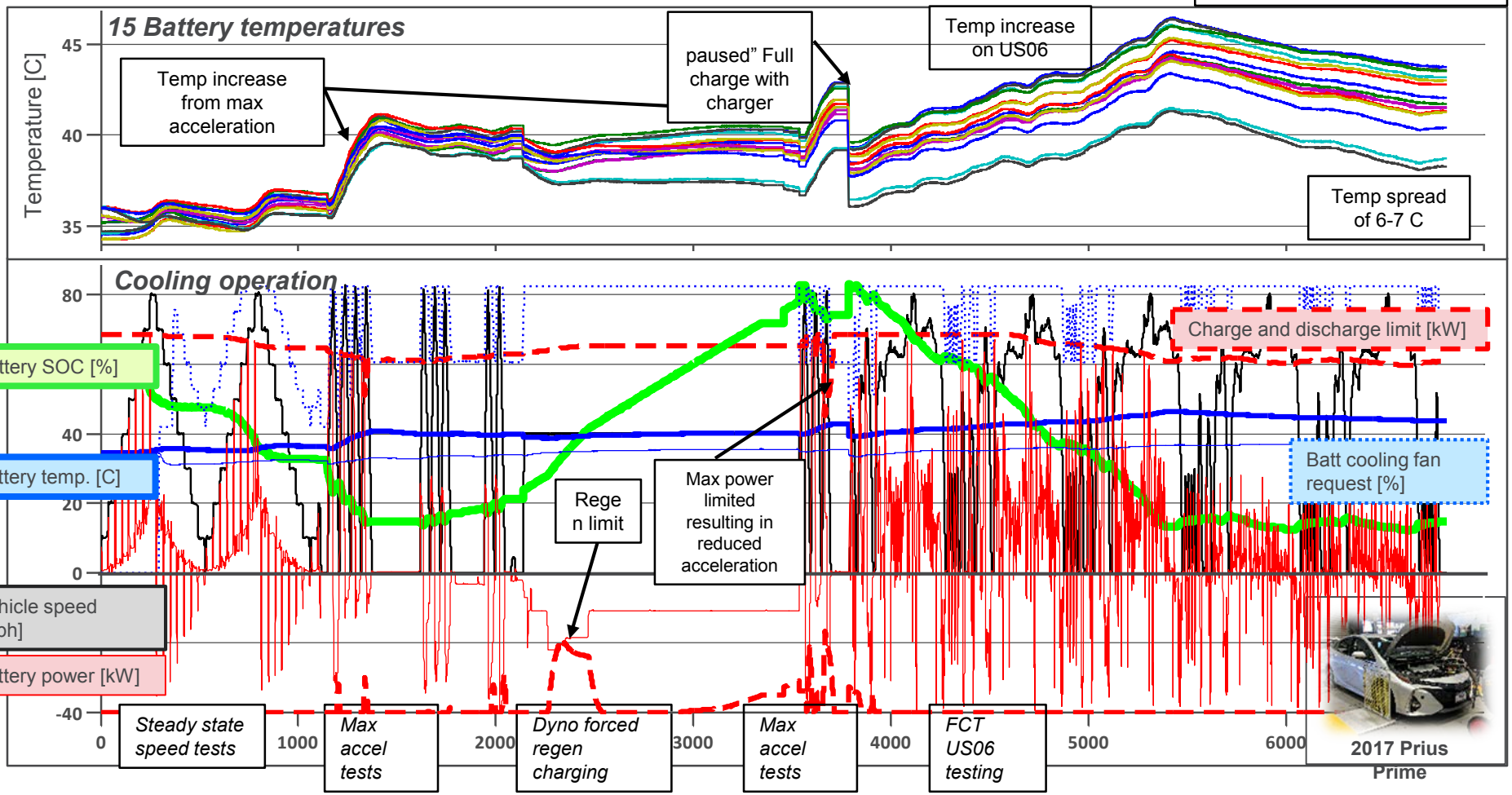
- Toyota 2ZR-FXE I4, 1.8L Engine
  - High-expansion ratio Atkinson cycle
  - 71kW @5200, 142Nm @3600
  - 16valve DOHC, VVT-I, cooled EGR, SFI
- THS-II, the next generation of the power split
  - MG1: 23kW / 40Nm (Gen, Eng Start)
  - MG2: 53kW / 163 Nm (Gen, Drive wheels)
  - **One way clutch enables dual motor operation**
  - Boost Converter to 600V
- 8.8kWh (25Ahr) Lithium Ion battery pack
  - 95 cells (19 cells x 5 stacks)
  - 351.5V Nominal, air cooled





AIR COOLED BATTERY PACK IN PRIUS PRIME

Testing Note: *Preceding testing include FCT US06 and charging which caused the elevated initial battery temperature*



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MEASURING SMALL CHANGES IN FUEL CONSUMPTION WITH CONFIDENCE IS DIFFICULT

- Establish statistical confidence
  - Repeats relative to expected change
- Powertrain thermal conditioning is critical
  - Consistent overnight soak period
  - Consistent time between tests
  - Consistent test plan day-to-day
- Considerations to minimize test to test variability
  - Vehicle on dyno for duration of testing
  - Robot driver (+ SAE J2951 metrics)
  - Same staff for consistency in daily execution (small nuances within standard procedures can have a small impacts on consumption)
  - 12V battery tender over night (removed for testing)
- Other factors considered
  - Hood closed, Vehicle fan in speed mode, weekend soak, vehicle loss determination, modal background, multiple fuel flow measurements in additional bags

Statistics

	Bag FC [L/100km]			
Test ID	Bag 1	Bag 2	Bag 3	Bag 4
61611072	10.168	9.439	9.471	9.448
61612001	10.134	9.451	9.475	
61612009	10.167	9.468	9.444	9.430
61612017	10.256	9.558	9.532	9.548
Avg	10.181	9.479	9.481	9.475
STD [%]	0.511	0.569	0.390	0.672
90% Confide	0.055	0.058	0.039	0.068

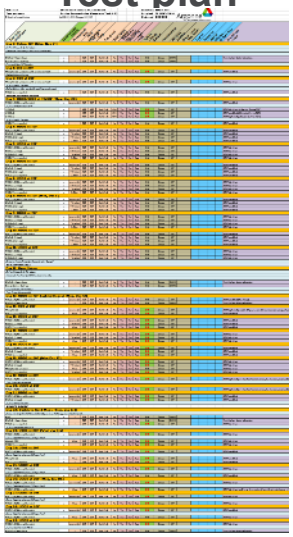
Sample size, mean, standard deviation and confidence interval calculations

Instrumentation

Fuel consumption:
- carbon balance + direct fuel flow

Vehicle analog+CAN:
- behavior changes

Test plan



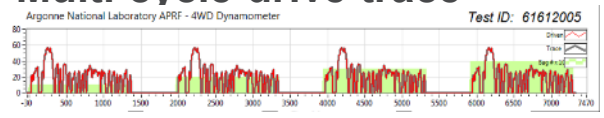
Consistent soaks and repeated days

Robot Driver

Consistency

Continuously on rolls for 29 test days and 2000+ miles

Multi cycle drive trace



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